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Characterization of hole-diameter in thin metallic plates perforated by spherical projectiles using genetic algorithms

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Abstract The empirical and semi-empirical models available in literature for the estimation of hole-diameter in thin metallic plates by the strike of spherical projectile are mostly valid for the data for which these have been developed. This may be partly attributed to the form of the model employed for their development. The behavioural constraints and the limiting conditions are not satisfied by these models. In the present paper, some of the non-dimensional models have been developed that satisfy the behavioural constraints and limiting conditions. The data used in the development of earlier statistical models has been reanalyzed for the development of new models for the characterization of hole-diameter with a view towards seeing whether better characterization is possible. The genetic algorithm coupled with the penalty function method has been used for the constrained optimization of model parameters that result in low errors and high correlation coefficients.

Keywords Genetic algorithm · Hole-diameter · Projectile · Hypervelocity impact · Spherical projectile

List of symbols

c_p, c_t	Speed of sound in projectile and target materials, respectively
ρ_p, ρ_t	Density of projectile and target materials, respectively
D_p	Diameter of spherical projectile
D_h	Hole-diameter in target plate
T_t	Target thickness
V	Velocity of strike of projectile
σ_{US}	Shear strength of the target material
θ	Angle of strike or spray angle of projectile

1 Introduction

Since the launch of Sputnik-1 in 1957, the first earth-orbiting Russian satellite, more than 4,000 successful launches have been conducted by the international space community. The on-orbit explosions and collisions are the major dominating contributors to the space debris. The man-made space debris of more than 9,000

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catalogued population consists of derelict spacecraft, spent rocket upper-stages, boost motor effluents, and debris from fragmentation events [1]. The scientists and engineers have emphasized that the number of debris objects will continue to increase as not only because of the annual increase in number of launches but mainly as a result of collisions between existing debris bodies. The increasing space debris and meteoroids pose severe threat of hypervelocity impact on the operational spacecrafts. Due to their potentially high speeds and collision energies, the impact of space debris can be critical to mission safety. The representation of the hole-diameter in the shield/plate or some other component of a spacecraft as a function of various projectile and target parameters helps in the assessment of its damage and hence its performance and functioning. The hole-diameter in thin targets may also give an idea about the characteristics of the projectile. When a meteoroid strikes the shield, it breaks the meteoroid, thus reducing the impact on the body of the spacecraft. The present study of spherical projectile finds its application in such impacts because the impacting debris or meteoroid may be replaced by an equivalent sphere [2,3]. The velocity range of interest to spacecraft industry is up to 18 km/s because the anticipated average impact velocity of orbital debris for spacecraft in low earth orbit is about 11 km/s and of micro-meteoroids is about 18 km/s.

The larger stresses occurring in hypervelocity impact permit neglect of rigidity and compressibility of the striking bodies, and the impact is viewed as fluid flow. The description of material properties is then greatly simplified, and correction terms are added to the original Bernoulli equation to account for target and projectile strength. Though such fluid mechanics–based analytical solutions for estimating hole-diameter under hypervelocity impact are available in literature [4,5], these models also involve empirical constants. The influence of body curvature of the target on the penetration hole size was included in [6], but its effect was found to be of the order of other uncertainties and was thus negligible. For the impact of spheres on plates, the morphology of lip structure was found to be dependant on the ratio of plate thickness to sphere diameter especially when this ratio is large. Many empirical relations based on the regression of available data are available in literature [7–9], but most of them are applicable for the data for which these have been developed. Despite the availability of large number of models, the problem of hole-diameter estimation has remained inconclusive. This may be partly attributed to the complexity of the phenomenon involved and partly due to the form of the model employed for their development [10]. The behavioural constraints and the limiting conditions are not satisfied by most of the models. In the present paper, some of the non-dimensional models have been developed that satisfy the behavioural constraints and limiting conditions through the use of genetic algorithm (GA) that make it possible to explore a far greater range of potential solutions to the problem. Another area in which GAs excel is their ability to manipulate many parameters simultaneously [11]. The data considered in the earlier studies has been reanalyzed with a view towards seeing whether better characterization is possible.

The GAs emulate the remarkable power of mechanism of biological evolution for the development of problem-solving strategy. The algorithm is capable of solving problems even when its structure is not fully understood. The GAs are intrinsically parallel, which allows them to implicitly evaluate many schemes at once, GAs are particularly well suited to solving problems where the space of all potential solutions is truly huge—too vast to search exhaustively in any reasonable amount of time. In the present work, this algorithm has been applied to the complex problem of characterizing growth of hole-diameter.

The data of several researchers [12–17] who carried out experimental investigations involving the impact of spherical projectiles on thin plates of the same or different material at impact velocity varying from 1 to 15 km/s using the light-gas guns has been used. The use of data covering a large range of projectile diameter, plate thickness and wide range of velocity greatly enhances the scope of the present study.

2 Perforation process

During the hypervelocity impact of non-deformable hemispherical projectiles on metallic plates, the failure mode seems to be strongly dependent on the impact velocity. Though the common failure mode of plates is petalling [18–22], it may be replaced by failure mode of crack opening when impact velocity is close to the ballistic limit. In this situation, a decrease in the circumferential strain slows the crack progression [21]. Moreover, when the impact velocity is very high, the perforation process is governed by inertia effects and the failure mode changes from petalling to complete fragmentation of the zone affected by impact, inducing appearance of debris cloud as final stage [17,23]. Teng et al. [24] have also observed the influence of the impact velocity on the failure mode during tests performed with Weldox 460 E steel cylinders. At relatively low impact velocity, no external cracks appeared in the specimen. On the contrary, for high initial impact